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# The Impact of Climate Change and Variability on Heavy Precipitation, Floods, and Droughts

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*There is a direct influence of global warming on changes in precipitation and heavy rains. Increased heating leads to greater evaporation and thus surface drying, thereby increasing intensity and duration of drought. However, the water-holding capacity of air increases by about 7% per 1 °C warming, which leads to increased water vapor in the atmosphere, and this probably provides the biggest influence on precipitation. Storms, whether individual thunderstorms, extratropical rain or snow storms, or tropical cyclones and hurricanes, supplied by increased moisture, produce more intense precipitation events that are widely observed to be occurring, even in places where total precipitation is decreasing. In turn, this increases the risk of flooding. Patterns of where it rains also have been observed to change, with dry areas becoming drier (generally throughout the subtropics) and wet areas becoming wetter, especially in mid to high latitudes. This pattern is simulated by climate models and is projected to continue into the future. Since more precipitation occurs as rain instead of snow with warming, and snow melts earlier, there is increased runoff and risk of flooding in early spring, but increased risk of drought in deep summer, especially over continental areas.*

## INTRODUCTION

Heated by the sun's radiation, the ocean and land surface evaporate water, which then moves around with winds in the atmosphere, condenses to form clouds, and falls back to the Earth's surface as rain or snow, only for some of it to flow to oceans *via* rivers, thereby completing the global hydrological (water) cycle.

Hydrological extreme events are typically defined as *floods and droughts*. Floods are associated with extremes in rainfall (from tropical storms, thunderstorms, orographic rainfall, widespread extratropical cyclones, etc.), while drought is associated with a lack of precipitation and often extreme high temperatures that contribute to drying. Floods are often fairly local and develop on short timescales, while droughts are extensive and develop over months or years. Both can be mitigated: floods by good drainage systems and drought by irrigation, for instance. Nonetheless, daily newspaper headlines of floods and droughts reflect the critical importance of the water cycle, in particular, precipitation, in human affairs. Flood damage estimates are in the billions of US dollars annually, with thousands of lives lost, while

drought costs are of similar magnitude and often lead to devastating wildfires and heat waves. An example is the extreme drought in California in 2007 that set the stage for the costly extensive wildfires in October 2007, with over 2000 houses burned and about 1 million people displaced. The loss of life and property from extreme hydrological events has therefore caused society to focus on the causes and predictability of these events. Tropical cyclones typically have the highest property damage loss of any extreme event, and are therefore of great interest to state and local disaster preparedness organizations, as well as the insurance industry (Murnane, 2004).

Precipitation varies from year to year and over decades, and changes in amount, intensity, frequency, and type (e.g. snow vs rain) affect the environment and society. Steady moderate rains soak into the soil and benefit plants, while the same rainfall amounts in a short period of time may cause local flooding and runoff, leaving soils much drier at the end of the day. Snow may remain on the ground for some months before it melts and there is runoff. These examples highlight the fact that the characteristics of precipitation are just as vital as the amount in terms

the effect on the soil moisture and stream flow. There is increasing evidence that human-induced climate change, “global warming”, is changing the precipitation and the hydrological cycles, especially the extremes. In this article, we discuss the conceptual basis for understanding changes in precipitation, floods and drought, the observational evidence for changes, and future prospects.

## PRECIPITATION PROCESSES AND THEIR CHANGES

*Precipitation* is the general term for rainfall, snowfall, and other forms of frozen or liquid water falling from clouds. Precipitation is intermittent, and the character of the precipitation, when it occurs, depends greatly on temperature and the weather situation. The latter determines the storms and supply of moisture through winds and surface evaporation, and how it is gathered together to form clouds. Precipitation forms as water vapor is condensed, usually in rising air that expands and hence cools. The upward motion comes from air rising over mountains, warm air riding over cooler air (warm front), colder air pushing under warmer air (cold front), convection from local heating of the surface, and other weather and cloud systems. Precipitation is, therefore, also dependent on the presence of storms of one sort or another.

As air warms to above freezing point, the precipitation turns to rain. However, a vital point is that the water-holding capacity of air increases 6–7% for every 1°C increase in temperature. This comes from a well-established physical law (the Clausius–Clapeyron equation). In winter, as temperatures drop below freezing point, the air becomes “freeze dried” and at very low temperatures, below –10°C, snow tends to become very light with small flakes or even “diamond-dust-like”. It is only when temperatures are near freezing that huge amounts of snow fall, flakes can be large, and snow can bind together so that one can make snow-men (or snow-women). The same process is essential for creating precipitation. As air rises into regions of lower pressure, it expands and cools, and that cooling causes water vapor to condense and precipitation to form. Consequently, changes in temperature provide a very fundamental constraint on precipitation amount and type through the water vapor content of the air.

The conceptual basis for changes in precipitation has been given by Trenberth (1998, 1999), Allen and Ingram (2002), Trenberth *et al.* (2003), and Held and Soden (2006). Issues relate to changes in location, type, amount, frequency, intensity and duration of precipitation, and especially changes in extremes. As climate varies or changes, several direct influences alter precipitation amount, intensity, frequency, and type.

Warming accelerates land-surface drying as heat goes into evaporation of moisture, and this increases the potential incidence and severity of droughts, which has been observed in many places worldwide (Dai *et al.*, 2004). The moisture in the atmosphere then gets carried around by atmospheric winds to where storms are favored. Typical storms reach out a distance of about four times the radius of the rain dimension, and gather in the water vapor, to produce precipitation (Trenberth, 1998, 1999). In weather systems, convergence of increased water vapor leads to more intense precipitation and the risk of heavy rain and snow events, but may also lead to reductions in duration and/or frequency of rain events, given that total amounts do not change much.

The basic theory, climate model simulations, and empirical evidence all confirm that warmer climates, owing to increased water vapor, lead to more intense precipitation events even when the total annual precipitation is reduced slightly, and with prospects for even stronger events when the overall precipitation amounts increase. A warmer climate, therefore, increases risks of both drought – where it is not raining – and floods – where it is raining – but at different times and/or places. For instance, the summer of 2002 in Europe brought widespread floods, but was followed by record-breaking heat waves and drought, a year later in 2003. In the Mediterranean (Alpert *et al.*, 2002), drought is often accompanied by stronger rainfall events. In the summer of 2007, from May to July, widespread flooding in central England (wettest since records began in 1766) was accompanied by drought and record-breaking heat waves (temperatures exceeding 40°C) in southeast Europe (see [http://www.wmo.ch/pages/mediacentre/press\\_releases/pr\\_791\\_e.html](http://www.wmo.ch/pages/mediacentre/press_releases/pr_791_e.html)).

Other changes occur as the patterns of where storms form and tracks change, and thus the global atmospheric circulation plays a key role as well in the distribution of precipitation (Trenberth, 1998, 1999; Vecchi *et al.*, 2006; IPCC, 2007). The distribution and timing of floods and droughts is most profoundly affected by the cycle of El Niño events, particularly in the tropics and over much of the midlatitudes of Pacific-rim countries.

Expectations for changes in overall precipitation amounts are complicated by aerosols. Since particulate aerosols block the sun, surface heating is reduced. Absorption of radiation by some – notably carbonaceous – aerosols directly heats the aerosol layer. Otherwise the layer may have been heated by latent heat release following surface evaporation. Hence these aerosols reduce the hydrological cycle. As aerosol influences tend to be regional, the expected net effect on precipitation over land is especially unclear. In areas where aerosol pollution masks the ground from direct sunlight, decreases in evaporation reduce the overall moisture supply to the atmosphere. The largest decrease recorded in global land precipitation followed in

the year after the Mount Pinatubo volcanic eruption, owing to cooling from the aerosol deposited in the stratosphere (Trenberth and Dai, 2007). Hence, even as the potential for heavier precipitation occurs from increased water vapor amounts, the duration and frequency of events may be curtailed, as it takes longer to recharge the atmosphere with water vapor.

Beyond climate impacts on extremes, local and regional weather factors play an important role in the production of extreme weather events. The recent studies of the Buffalo Creek flood (Chen *et al.*, 2001) provide evidence that burned regions in a river basin can be preferred regions for flash-flood formation. Mesoscale model simulations indicated preferred cloud and precipitation formation over the burn region due to enhanced sensible heat flux. The sensible heat flux was increased owing to the darker soil and low water content in the soil after the fire. Runoff was also increased owing to the more impervious soil and decreased vegetation. Moisture advection into the region was affected by farm irrigation within 100 km of the site. Thus, local and mesoscale features of river basins (especially characteristics of the soil and vegetation and its coupling to the boundary layer and clouds) may play an important role in extreme weather events, especially flood formation.

## OBSERVATIONS OF CHANGE

### Water Vapor

In the lower troposphere, condensation of water vapor into precipitation provides latent heating, which dominates the structure of tropospheric diabatic heating (Trenberth and Stepaniak, 2003a,b). Water vapor is also the most important gaseous source of infrared opacity in the atmosphere, accounting for about 60% of the natural greenhouse effect for clear skies (Kiehl and Trenberth, 1997), and provides the largest positive feedback in the model projections of climate change (Held and Soden, 2000; Karl and Trenberth, 2003).

Water vapor at the land surface has been measured since the late nineteenth century, but only observations made since the 1950s have been compiled into a database suitable for climate studies. The network of radiosonde measurements provides the longest record of water vapor measurements in the atmosphere, dating back to the mid-1940s. However, early radiosonde sensors suffered from significant measurement biases, particularly for the upper troposphere, and changes in instrumentation with time often lead to artificial discontinuities in the data record (Elliott *et al.*, 2002). Consequently, most of the analysis of radiosonde humidity has focused on trends for altitudes below 500 hPa and are restricted to those stations and periods for which stable instrumentation and reliable moisture soundings are available.

Additional information on water vapor can be obtained from satellite observations and atmospheric reanalysis products since 1979. Satellite observations provide near-global coverage and thus represent an important source of information over the oceans, where radiosonde observations are scarce, and in the upper troposphere, where radiosonde sensors are often unreliable.

Dai (2006a,b) analyzed near-global (60°S–75°N) synoptic weather data for 1976–2005 from ships and buoys and over 15 000 land stations for specific humidity, temperature, and relative humidity. Nighttime relative humidity was found to be greater than daytime relative humidity by 2–15% over most land areas, as temperatures undergo a diurnal cycle, while moisture does not change much. The global trends of near-surface relative humidity are very small. Trends in specific humidity tend to follow surface temperature trends with a global average increase of 0.06 g per kg per decade (1976–2004). The rise in specific humidity corresponds to about 4.9% per 1°C warming over the globe. Over the ocean, the observed surface specific humidity increases at 5.7% per 1°C warming, consistent with a constant relative humidity. Over land, the rate of increase is slightly smaller (4.3% per 1°C), suggesting a modest reduction in relative humidity as temperatures increase, as expected in water-limited regions.

For the lower troposphere, water vapor information has been available from TOVS since 1979 and the scanning multichannel microwave radiometer (SMMR) from 1979 to 1984. Here TOVS is the TIROS series of operational vertical sounder where TIROS is Television Infrared Observation Satellites. However, the main improvement occurred with the introduction of the special sensor microwave imager (SSM/I) in mid-1987. Retrievals of column-integrated water vapor from SSM/I are generally regarded as providing the most reliable measurements of lower tropospheric water vapor over the oceans, although issues pertaining to the merging of records from successive satellites do arise (Trenberth *et al.*, 2005; Sohn and Smith, 2003).

Significant interannual variability of column-integrated water vapor has been observed, with increases during El Niño events (Soden and Schroeder, 2000; Allan *et al.*, 2003; Trenberth *et al.*, 2005) and reduction by a smaller magnitude in response to global cooling following the eruption of Mt. Pinatubo in 1991 (Soden *et al.*, 2002; Trenberth and Smith, 2005). The linear trend based on monthly SSM/I data over the oceans was 1.2% per decade (0.40 ± 0.09 mm per decade) for 1988–2004 (Trenberth *et al.*, 2007; Santer *et al.*, 2007). As noted by Trenberth *et al.* (2005), most of the patterns associated with the interannual variability and linear trends can be reproduced from the observed sea surface temperature (SST) changes over this period by assuming a constant relative humidity increase in water vapor mixing ratio. Given observed SST

increases, this implies an overall increase in water vapor of order 5% over the twentieth century and about 4% since 1970.

In the upper troposphere, the available data suggest that there is no detectable trend in upper-tropospheric relative humidity (Soden *et al.*, 2005). However, given an observed increase in tropospheric temperatures, this implies an increase in specific humidity and thus in moisture amount. Therefore, now, there is also evidence for global increases in upper-tropospheric specific humidity over the past two decades.

Hence observational evidence suggests that the relative humidity has tended to remain about the same, from the surface throughout the troposphere, and thus actual moisture amounts in the atmosphere increase at the same rate as the Clausius–Clapeyron equation gives, or about  $7\% \text{ K}^{-1}$  over the oceans where moisture supply is not limited (Trenberth *et al.*, 2005; Dai, 2006b; Soden *et al.*, 2005). Over land, where moisture sources are restricted, especially in arid regions, the increases are somewhat less (Dai, 2006b). The result is more moisture for storms to reach out and gather in, creating heavier rainfalls – or snowfalls – and thus potential for more flooding (Trenberth *et al.*, 2003). Santer *et al.* (2007) have identified a strong human influence in the recent water vapor increases.

## Precipitation

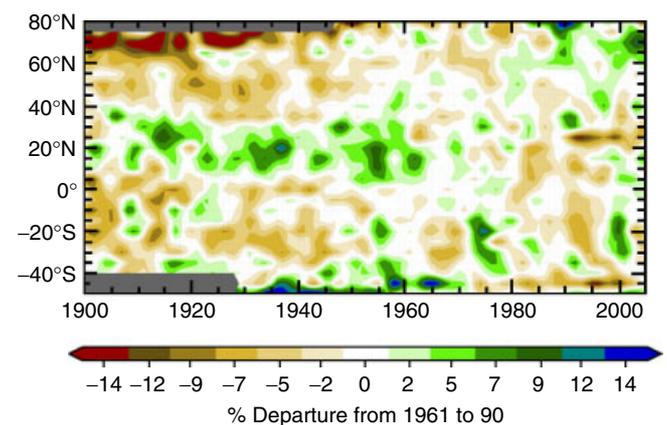
Difficulties in the measurement of precipitation remain an area of concern in quantifying the extent to which global and regional scale precipitation have changed. *In situ* measurements are especially impacted by wind effects on the gauge catch, especially for snow and light rain (Adam and Lettenmaier, 2003), and few measurements exist in areas of steep and complex topography (Adam *et al.*, 2006). For remotely sensed measurements (radar- and space-based), the greatest problems are that only measurements of instantaneous rate can be made and there are uncertainties in algorithms for converting radiometric measurements (radar, microwave, and infrared) into precipitation rates at the surface. To gain confidence in observations, it is useful to examine the consistency of changes in a variety of complementary moisture variables, including both remotely sensed and gauge-measured precipitation, drought, evaporation, atmospheric moisture, soil moisture, and stream flow, although uncertainties exist with all of these variables as well (Huntington, 2006).

A comprehensive summary of observed changes in precipitation is given in the Fourth Intergovernmental Panel on Climate Change assessment (Trenberth *et al.*, 2007), and the reader is referred there for the extensive bibliography. Schlosser and Houser (2007) and Wentz *et al.* (2007) provide recent estimates of precipitation and their trends. However, the precipitation and evaporation estimates of Schlosser and Houser (2007) are out of balance and reveal

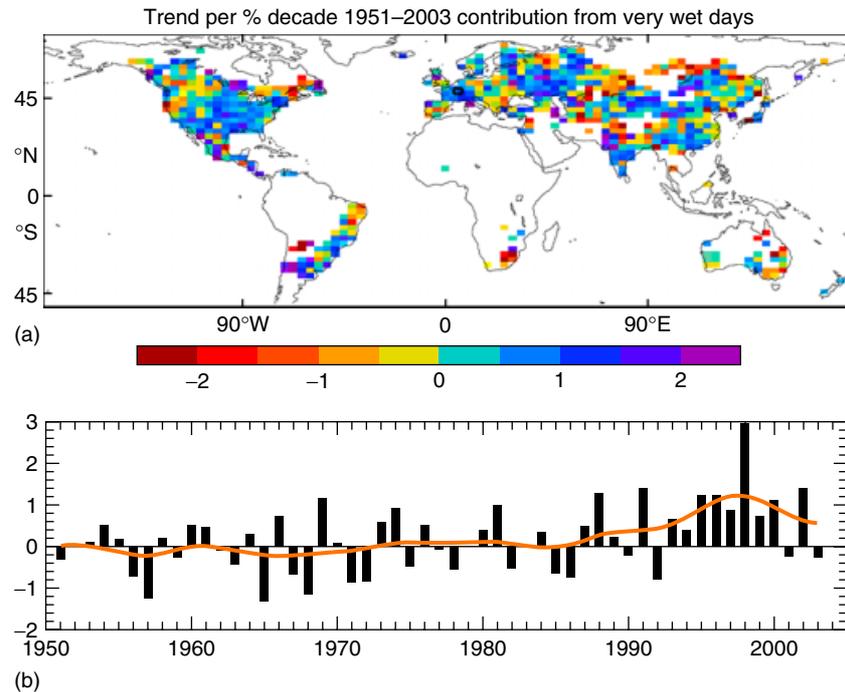
likely spurious changes over time associated with changes in satellites. The Wentz *et al.* (2007) estimates of trends may be too high as they are similarly affected and may also be influenced by the limited sample period. Gu *et al.* (2007) have documented global and tropical rainfall changes using the global precipitation climatology project (GPCP) and find near-zero global changes but with large variability and changes over land that are largely compensated for by opposite changes over the oceans. This is especially the case for El Niño events (Trenberth and Dai, 2007). Volcanic events are more likely to cause a net decrease in precipitation globally.

Precipitation often occurs on small scales, and large differences in individual rain events can occur over tens of kilometers. Variations are also large on short time frames as the weather evolves. Nonetheless, there are broad-scale patterns of precipitation related to preferred storm tracks. Moreover, recently there have emerged some large-scale patterns of change of precipitation amounts that appear to be linked to climate change.

Precipitation has generally increased at high northern latitudes north of about  $40^\circ\text{N}$  over the twentieth century and decreased since about 1950 in the tropics and subtropics, and especially from  $10^\circ\text{S}$  to  $30^\circ\text{N}$  (see Figure 1; Trenberth *et al.*, 2007). In particular, it has become significantly wetter in the eastern parts of North and South America, northern Europe, and northern and central Asia, in part, because higher temperatures increase water-holding capacity and more precipitation falls as rain instead of snow (Trenberth and Shea, 2005), but drier in the Sahel, the Mediterranean, southern Africa, and parts of southern Asia. In the more northern regions, more precipitation falls as rain



**Figure 1** Latitude–time section of zonal average annual anomalies for precipitation (%) over land from 1900 to 2005, relative to their 1961–1990 means. The values are smoothed with a  $1/12(1-3-4-3-1)$  filter to remove fluctuations less than about six years. The color scale is nonlinear and gray areas indicate missing data (From Trenberth *et al.* (2007) and reproduced by permission of IPCC)



**Figure 2** (a) Observed trends percentage per decade for 1951–2003 for the contribution to total annual precipitation from very wet days corresponding to the 95th percentile. Trends were only calculated for grid boxes where both total and the 95th percentile had at least 40 years of data during this period and had data until at least 1999. (b) Anomalies of the global annual time series (with respect to 1961–1990) defined as *the percentage change of very wet day contribution from the base period average (22.5%)*. The red line shows decadal variations (Reprinted from Trenberth *et al.* (2007), as adapted from Alexander *et al.* (2006), and reproduced by permission of IPCC)

rather than snow (e.g. Mote, 2003; Knowles *et al.*, 2006). The liquid-precipitation season has become longer by up to three weeks in some regions of the boreal high latitudes over the last 50 years (Trenberth *et al.*, 2007) owing, in particular, to an earlier onset of spring. Basin-scale changes in ocean salinity provide further evidence of changes in the Earth's water cycle, with freshening at high latitudes and increased salinity in the subtropics.

As noted by IPCC (Trenberth *et al.*, 2007), there is also clear evidence of changes in the extremes of precipitation. For the contiguous United States, Kunkel *et al.* (2003) and Groisman *et al.* (2004) find statistically significant increases in heavy (upper 5%) and very heavy (upper 1%) precipitation, by 14 and 20%, respectively. Much of this increase occurred during the last three decades of the century, especially over the eastern parts of the country. Also, there is new evidence for Europe and the United States that the relative increase in precipitation extremes is larger than the increase in mean precipitation, and this is manifested as an increasing contribution of heavy events to total precipitation (Klein Tank and Können, 2003; Groisman *et al.*, 2004).

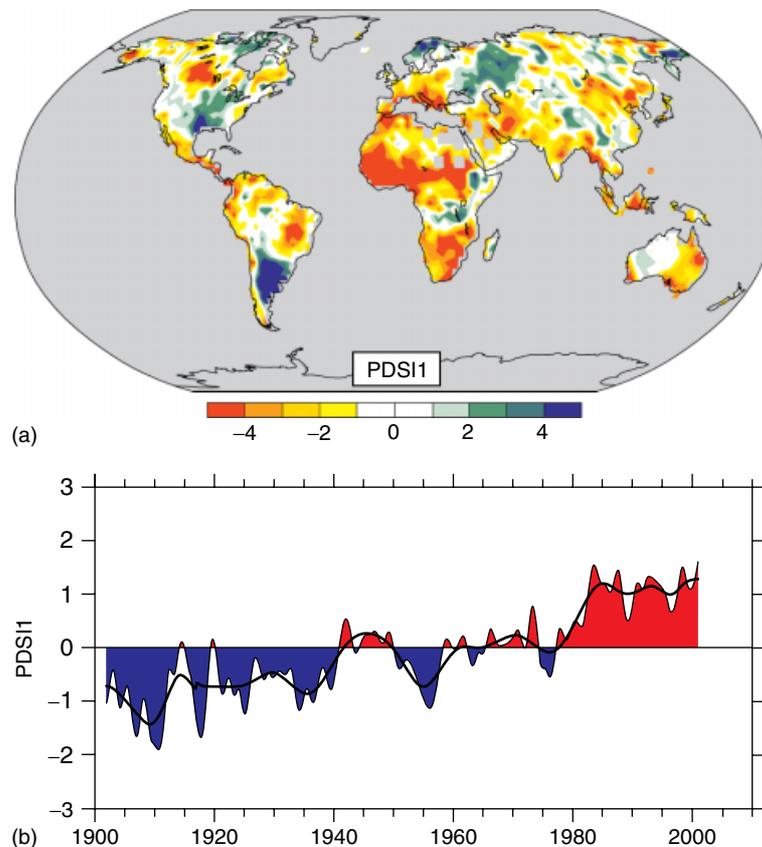
The main global compilations of changes in extreme precipitation are from Alexander *et al.* (2006) and Groisman *et al.* (2005), complemented by Peterson *et al.* (2002) and

Klein Tank *et al.* (2006); see Figure 2. Globally averaged over the land area with sufficient data, the percentage contribution to total annual precipitation from very wet days (upper 5%) has increased in the past 50 years (Figure 2), even in places where mean precipitation amounts are not increasing. For very heavy precipitation events, increasing trends are reported as well, but results are available for only a few areas.

While enhanced rainfall rates increase the risk of flooding, mitigation of flooding by local councils and government bodies (such as the Corps of Engineers and the Bureau of Reclamation in the United States) is continually occurring, and flooding records are often confounded by changes in land use and increasing human settlement in flood plains. Nevertheless, great floods have been found to be increasing in the twentieth century (Milly *et al.*, 2002).

## Drought

Drought is easier to measure because of its long duration. While there are numerous indices and metrics of drought, many studies use monthly precipitation totals and temperature averages combined into a measure called the *Palmer Drought Severity Index (PDSI)*. The PDSI calculated from the middle of the twentieth century shows a



**Figure 3** The most important spatial pattern (a) of the monthly Palmer Drought Severity Index (PDSI) for 1900–2002. The PDSI is a prominent index of drought and measures the cumulative deficit (relative to local mean conditions) in surface land moisture by incorporating previous precipitation and estimates of moisture drawn into the atmosphere (based on atmospheric temperatures) into a hydrological accounting system. (b) The panel shows how the sign and strength of this pattern has changed since 1900. Red and orange areas are drier (wetter) than average and blue and green areas are wetter (drier) than average when the values shown in the lower plot are positive (negative). The time series approximately corresponds to a trend, and this pattern and its variations account for 67% of the linear trend of PDSI from 1900 to 2002 over the global land. It therefore features widespread increasing African drought, especially in the Sahel, for instance. Note also the wetter areas, especially in eastern North and South America, and northern Eurasia (Reprinted from Trenberth *et al.* (2007), as adapted from Dai *et al.* (2004), and reproduced by permission of IPCC)

large drying trend over many Northern Hemisphere land areas since the mid-1950s, with widespread drying over much of southern Eurasia, northern Africa, Canada, and Alaska (Dai *et al.*, 2004; Figure 3), and an opposite trend in eastern North and South America. In the Southern Hemisphere, land surfaces were wet in the 1970s and relatively dry in the 1960s and 1990s, and there was a drying trend from 1974 to 1998. Decreases in precipitation over land since the 1950s are the likely main cause for the drying trends, although large surface warming during the last two to three decades has also likely contributed to the drying by increasing atmospheric demand for moisture. Drought has increased especially throughout Africa, southern Asia, the southwestern United States, Australia, and the Mediterranean region (both southern Europe and northern Africa), and has also influenced the Amazon. Dai *et al.* (2004) show that very dry land areas across the globe (defined

as areas with PDSI less than  $-3.0$ ) have more than doubled in extent since the 1970s, associated with an initial El Niño/Southern Oscillation (ENSO)-related precipitation decrease over land and with subsequent increases primarily due to surface warming.

### Patterns of Change

Local and regional changes in the character of precipitation depend a great deal on atmospheric circulation patterns of variability. Some of these observed circulation changes are associated with climate change. An associated shift in the storm track makes some regions wetter and some – often nearby – drier, making for complex patterns of change. The distribution and timing of floods and droughts is most profoundly affected by the cycle of El Niño events, particularly in the tropics and over much of

the midlatitudes of Pacific-rim countries (Diaz and Markgraf, 2000). For instance, opposite phases of ENSO were shown by Trenberth and Guillemot (1996) to play a role in the 1988 drought and 1993 floods in North America. They showed that both the 1988 drought and 1993 floods developed as a result of a change in the large-scale atmospheric circulation in the Pacific and across North America that altered the storm tracks into North America. ENSO altered the tropical SSTs and therefore the atmospheric convection, which in turn changed the latent heating pattern and the quasi-stationary planetary wave pattern, the jet stream location, and the associated storm track.

In recent years, the patterns of precipitation change have developed a distinctive pattern whereby higher latitudes have become wetter and the subtropics and much of the tropics have become drier. The exception is the monsoon trough in the tropics that denotes the wet season. This distinctive pattern of change is associated with changes in atmospheric circulation (Trenberth *et al.*, 2007), in particular, increases in the westerly winds in midlatitudes associated with preferred patterns of behavior, sometimes called *modes*. In the Northern Hemisphere, it is the Northern Annular Mode (NAM) (Thompson and Wallace, 1998) and in the Southern Hemisphere it is the Southern Annular Mode (SAM); see Trenberth *et al.*, (2007). The NAM is closely related to another phenomenon called the *North Atlantic Oscillation* (NAO), which is a more regional measure of westerly wind strength over the North Atlantic, mainly in winter. In the European sector, a more positive NAO in the 1990s led to wetter conditions in northern Europe and drier conditions over the Mediterranean and northern African regions (Hurrell *et al.*, 2003).

The prolonged drought in the Sahel, which was pronounced from the late 1960s to the late 1980s, continues although it is not quite as intense as it was; it has been linked, through changes in atmospheric circulation, to changes in tropical SST patterns in the Pacific, Indian, and Atlantic basins (Giannini *et al.*, 2003; Hoerling *et al.*, 2006). Drought has become widespread throughout much of Africa and more common in the tropics and subtropics.

### Runoff and Streamflow

Available streamflow gauge records cover only about two-thirds of the global actively drained land areas and they often have gaps and vary in record length (Dai and Trenberth, 2002). Estimates of total continental river discharge are, therefore, often based on incomplete gauge records and how missing values are dealt with can often determine the results. Streamflow records for the world's major rivers show large decadal to multidecadal variations, with small secular trends for most rivers. Increased streamflow during the later half of the twentieth century has been reported over regions with increased precipitation (e.g. Groisman

*et al.*, 2004). Further, Milly *et al.* (2002) show significant trends toward more extreme flood events from streamflow measurements on 29 very large basins.

Dai *et al.* (2008) have produced a new comprehensive global synthesis of trends in runoff and river discharge into the oceans using 925 stream gauge records for the period 1948–2004. The results alter some earlier published results (Gedney *et al.*, 2006) as there is large sensitivity to how missing data are treated. Results revealed large variations in continental discharge at interannual to decadal timescale correlated with ENSO for the discharge into the Pacific, Atlantic, Indian, and global oceans as a whole (but not with discharges into the Arctic Ocean, and the Mediterranean and Black Seas). There is a large upward trend in the water-year discharge into the Arctic Ocean from 1949 to 2004. For the other ocean basins and the global oceans as a whole, the discharge data show downward trends and precipitation changes are found to be the main cause. For the Arctic drainage areas, upward trends in streamflow are not accompanied by increasing precipitation, especially over the Siberia, and decreasing trends in snow cover and soil ice water content over the northern high latitudes may contribute to the runoff increases in these regions.

### Evaporation

Estimates of evaporation can be made using bulk flux formulae but are difficult to achieve with reliability. Schlosser and Houser (2007) and Wentz *et al.* (2007) have both made recent estimates of evaporation and precipitation trends over the ocean and find increases since the late 1980s, which are associated especially with increased winds. However, the main change occurs in association with a change in SSM/I satellites and is likely spurious (Schlosser and Houser, 2007). Perhaps the most reliable and vetted evaporation dataset comes from Yu and Weller (2007), which finds that increases in surface evaporation appear to be real.

### PROSPECTS FOR THE FUTURE

The main predictable component of climate change in the future is that associated with human activities (IPCC, 2007). Humans are changing the composition of the atmosphere by adding carbon dioxide and visible particulates, called *aerosols*, mainly by burning fossil fuels. Other activities add methane and nitrous oxide, which along with carbon dioxide are greenhouse gases, so that they trap outgoing infrared radiation and warm the planet (IPCC, 2007). The effect is of order 1% of the natural flow of energy through the climate system (Karl and Trenberth, 2003). Changes in radiative forcing associated with increasing greenhouse gases in the atmosphere produce increased heating at the surface. The actual amount of heating depends critically on various feedbacks, including water vapor feedback,

ice–albedo feedback, and effects of changes in clouds (Karl and Trenberth, 2003). One consequence of increased heating from the human-induced, enhanced greenhouse effect is increasing temperature. However, another consequence is increased evaporation of surface moisture (Yu and Weller, 2007), thereby changing the hydrological cycle, provided adequate surface moisture is available (as it always is over the oceans and other wet surfaces). Santer *et al.* (2007) have identified a strong human influence in the recent water vapor increases. Hence, surface moisture effectively acts as an “air conditioner”, as heat used for evaporation acts to moisten the air rather than warm it. An observed consequence of this partitioning is that summers, in particular, generally tend to be either warm and dry or cool and wet (Trenberth and Shea, 2005).

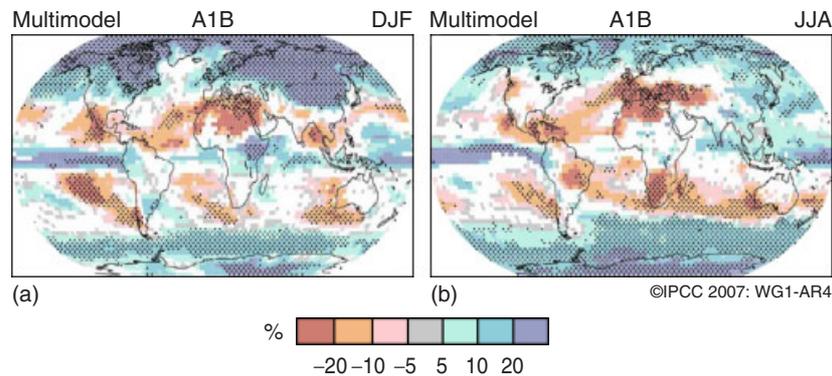
For precipitation, climate models typically predict an increase in amount globally of 1–2% per 1°C warming in global mean temperature, although this value is quite uncertain (Allen and Ingram, 2002). A very robust finding in all climate models with global warming is for an increase in potential evapotranspiration. In the absence of precipitation, this leads to increased risk of drought, as surface drying is enhanced. It also leads to increased risk of heat waves and wildfires in association with such droughts; because once the soil moisture is depleted, all the heating goes toward raising temperatures and wilting plants.

The increase in surface evaporation depends on the energy available and the rate is much less than the 7% per 1°C increase in water vapor, although Wentz *et al.* (2007) suggest that this may be underestimated in models. A consequence is that the characteristics of precipitation must change (Trenberth *et al.*, 2003). As heavy rainfall rates typically greatly exceed local surface evaporation rates, the precipitation depends primarily on low-level moisture convergence. Therefore, the intensity of precipitation increases with the amounts of water vapor. In fact, the rate of increase can even exceed this because the additional latent heat released feeds back and invigorates the storm that causes the rain in the first place, further enhancing the convergence of moisture. However, the total precipitation amount increases at a much lower rate, and so the frequency or duration must decrease. In addition, as heat is transported upward during precipitation, there is greater latent heat released with more moisture and thus less need for the overall circulation to be as vigorous (Held and Soden, 2006; Vecchi *et al.*, 2006). One implication is that there must be a decrease in light and moderate rains, and/or a decrease in the frequency of rain events, as found by Hennessey *et al.* (1997). Thus, the prospect may be for fewer but more intense rainfall – or snowfall – events. Another implication is that large-scale overturning circulations, such as the Hadley and Walker cells, are apt to weaken.

These aspects are being explored in climate models. Often, daily mean amounts are used and may be analyzed in terms of the “shape” and “scale” parameters of a gamma distribution fit to the data. Wilby and Wigley (2002) use this approach to demonstrate increases in the extremes of precipitation with anthropogenic forcing in the NCAR climate system model and the Hadley Centre coupled model (HadCM2) in spite of quite different spatial patterns of precipitation change. Expectations outlined here are realized in the ECHAM4/OPYC3 model (Semenov and Bengtsson, 2002). Another check of this was performed in the Hadley Centre model (Allen and Ingram, 2002) and it indeed shows at the time of doubling of carbon dioxide, in the model simulations, that rainfall intensities less than about the 85th percentile decrease in frequency, while heavy events increase at close to the Clausius–Clapeyron rate. An analysis of the future climate simulations by the latest generation of coupled climate models (Sun *et al.*, 2007) shows that globally for each 1°C of surface warming, atmospheric precipitable water increases by ~9% and daily precipitation intensity increases by ~2%, whereas daily precipitation frequency decreases by 0.7%. However, for very heavy precipitation (>50 mm per day), the percentage increase in frequency is much larger than in intensity (31.2% vs. 2.4%) so that there is a shift toward increased heavy precipitation. On the basis of model results, IPCC (2007) finds that there is a tendency for an increase in daily heavy rainfall events in many regions, including some in which the mean rainfall is projected to decrease. In the latter cases, the rainfall decrease is often attributable to a reduction in the number of rain days rather than the intensity of rain when it occurs.

Hence, extreme weather events such as heavy rainfall (and thus floods) are projected to become much more frequent, as the climate warms. These aspects have enormous implications for agriculture, hydrology, and water resources, yet they have not been adequately appreciated or addressed in many studies of the impacts of climate change.

With regard to patterns of precipitation, climate model results from the IPCC (2007) assessment have become more consistent with regard to projected changes in precipitation and can now simulate recent observed patterns of change. Increases in the amount of precipitation are very likely at high latitudes. By late twentieth century, nearly all models projected increased precipitation over most of northern North America and also over northern Europe and Asia (Figure 4). At the same time, decreased precipitation is projected over Central America, southern Europe, and Mediterranean Africa. In southern Asia, there is a distinctive monsoonal signature to projected changes. In both North America and Europe, summer drying is extensive due to both the poleward movement of storms and increased evaporation. In the Southern Hemisphere, the strongest



**Figure 4** Relative changes in precipitation (in percent) for the period 2090–2099, relative to 1980–1999. Values are multimodel averages based on the special report on emissions scenarios (SRES) A1B scenario for December–February (a) and June–August (b). White areas are where less than 66% of the models agree in the sign of the change and stippled areas are where more than 90% of the models agree in the sign of the change (From IPCC (2007) and reproduced by permission of IPCC)

drying is projected for Brazil and southern Africa in winter (Figure 4).

Hence, in the Northern Hemisphere, for the twenty-first century, a robust pattern of increased precipitation poleward of about  $45^{\circ}\text{N}$  is projected due to the increase in water vapor in the atmosphere and the resulting increase in vapor transport from lower latitudes. This is accompanied by decreased subtropical precipitation, although less so, over Asia (Figure 4). Extratropical storm tracks are projected to move poleward, with consequent changes in wind, precipitation, and temperature patterns, continuing the broad pattern of observed trends over the last half-century. Along with a poleward expansion of the subtropical high-pressure systems, this leads to a drying tendency in the subtropics that is especially pronounced at the higher latitude margins of the subtropics.

The IPCC (2007) also concludes that future tropical cyclones (typhoons and hurricanes) will likely become more intense, with larger peak wind speeds and more heavy precipitation associated with ongoing increases of tropical SSTs. Since an intense tropical cyclone takes heat out of the ocean and mixes the ocean, leaving behind a much stronger cold wake than a more modest storm, there may be fewer tropical cyclones as a whole. Possible increases in static stability also lead to fewer tropical cyclones. Nonetheless, increased risk of flooding is a likely outcome from land-falling tropical storms.

As temperatures rise, the likelihood of precipitation falling as rain rather than snow increases, especially in autumn and spring at the beginning and end of the snow season, and in areas where temperatures are near freezing. Such changes are already observed in many places, especially over land, in middle and high latitudes of the Northern Hemisphere, leading to increased rains but reduced snowpacks, and consequently diminished water resources in summer, when they are most needed (e.g. Mote, 2003;

Knowles *et al.*, 2006). In extratropical mountain areas, the winter snowpack forms a vital resource, not only for skiers but also as a freshwater resource in the spring and summer as the snow melts. Yet warming makes for a shorter snow season with more precipitation falling as rain rather than snow, earlier melting of the snow that does exist, and greater evaporation and ablation. These factors all contribute to diminished snowpacks. In the summer of 2002, in the western parts of the United States, exceptionally low snowpacks and subsequent low soil moisture likely contributed substantially to the widespread intense drought because of the importance of recycling.

As can be seen from the above, finding out what is happening to precipitation and storms is vital. Fortunately, recent and continuing advancement of remote sensing (such as those on the Tropical Rainfall Measurement Mission and a proposed constellation of similar satellites) and innovative global precipitation retrieval techniques are becoming more capable of measuring precipitation variations with relatively high spatial and temporal scales. Global analyses of precipitation every 3–6 h are becoming available and prospects for hourly precipitation analyses are real. These efforts provide a potential data source to address variability on heavy precipitation, in terms of their intensities and frequencies, across various climate regions. Establishing what has happened to precipitation characteristics as well as how they are changing is essential for society.

It is evident from the above that climate change has large direct impacts on several aspects of the hydrological cycle and, in particular, increases extremes, making managing and using water resources more challenging. Dealing with drought one year, and then floods the next (as in Europe in 2002 and 2003), makes for major challenges for water managers on how to save in times of excess for those times when there is too little.

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## FURTHER READING

Soden B.J. (2000) The sensitivity of the tropical hydrological cycle to ENSO. *Journal of Climate*, **13**, 538–549.

## REFERENCES

- Adam J.C., Clark E.A., Lettenmaier D.P. and Wood E.F. (2006) Correction of global precipitation products for orographic effects. *Journal of Climate*, **19**, 15–38.
- Adam J.C. and Lettenmaier D.P. (2003) Adjustment of global gridded precipitation for systematic bias. *Journal of Geophysical Research*, **108**, 4257, DOI:10.1029/2002JD002499.
- Alexander L.V., Zhang X., Peterson T.C., Caesar J., Gleason B., Klein Tank A., Haylock M., Collins D., Trewin B., Rahimzadeh F., *et al.* (2006) Global observed changes in daily climate extremes of temperature and precipitation. *Journal of Geophysical Research*, **111**, D05109, DOI:10.1029/2005JD006290.
- Allan R.P. and Ringer M.A. and Slingo A. (2003) Evaluation of moisture in the Hadley Centre climate model using simulations of HIRS water vapour channel radiances. *Quarterly Journal of the Royal Meteorological Society*, **128**, 1–18.
- Allen M.R. and Ingram W.J. (2002) Constraints on future changes in climate and the hydrologic cycle. *Nature*, **419**, 224–232.
- Alpert P., Ben-Gai T., Baharad A., Benjamini Y., Yekutieli D., Colacino M., Diodato L., Ramis C., Homar V., Romero R., *et al.* (2002) The paradoxical increase of Mediterranean extreme daily rainfall in spite of decrease in total values. *Geophysical Research Letters*, **29**(11), DOI:10.1029/2001GL013554.
- Chen F., Warner T. and Manning K. (2001) Sensitivity of orographic moist convection to landscape variability: a study of the Buffalo Creek, Colorado, flash flood case of 1996. *Journal of the Atmospheric Sciences*, **58**, 3204–3223.
- Dai A. (2006a) Precipitation characteristics in eighteen coupled climate models. *Journal of Climate*, **19**, 4605–4630.
- Dai A. (2006b) Recent climatology, variability and trends in global surface humidity. *Journal of Climate*, **19**, 3589–3606.
- Dai A., Qian T., Trenberth K.E. and Milliman J.D. (2008) Changes in continental freshwater discharge from 1949–2004. *Journal of Climate*, (submitted).
- Dai A. and Trenberth K.E. (2002) Estimates of freshwater discharge from continents: latitudinal and seasonal variations. *Journal of Hydrometeorology*, **3**, 660–687.
- Dai A.G., Trenberth K.E. and Qian T. (2004) A global dataset of Palmer Drought severity index for 1870–2002: relationship with soil moisture and effects of surface warming. *Journal of Hydrometeorology*, **5**, 1117–1130.
- Diaz H.F. and Markgraf V. (Eds.) (2000) *El Niño and the Southern Oscillation, Multiscale Variability and Global and Regional Impacts*, Cambridge University Press, p. 496.
- Elliott W.P., Ross R.J. and Blackmore W.H. (2002) Recent changes in NWS upper-air observations with emphasis on changes from VIZ to Vaisala radiosondes. *Bulletin of the American Meteorological Society*, **83**, 1003–1017.
- Gedney N., Cox P.M., Betts R.A., Boucher O., Huntingford C. and Stott P.A. (2006) Detection of a direct carbon dioxide effect in continental river runoff records. *Nature*, **439**, 835–838.
- Giannini A., Saravanan R. and Chang P. (2003) Ocean forcing of Sahel rainfall on interannual to interdecadal time scales. *Science*, **302**, 1027–1030.
- Groisman P.Ya., Knight R.W., Easterling D.R., Karl T.R., Hegerl G.C. and Razuvaev V.N. (2005) Trends in intense precipitation in the climate record. *Journal of Climate*, **18**, 1326–1350.
- Groisman P.Ya., Knight R., Karl T., Easterling D.R., Sun B. and Lawrimore J. (2004) Contemporary changes of the hydrological cycle over the contiguous United States: trends derived from *in situ* observations. *Journal of Hydrometeorology*, **5**, 64–85.
- Gu G., Adler R.F., Huffman G.J. and Curtis S. (2007) Tropical rainfall variability on interannual-to-interdecadal/longer-time scales derived from the GPCP monthly product. *Journal of Climate*, **20**, 4033–4046.
- Held I.M. and Soden B.J. (2000) Water vapor feedback and global warming. *Annual Reviews of Energy Environment*, **25**, 441–475.
- Held I.M. and Soden B.J. (2006) Robust responses of the hydrological cycle to global warming. *Journal of Climate*, **19**, 5686–5699.
- Hennessy K.J. and Gregory J.M. and Mitchell J.F.B. (1997) Changes in daily precipitation under enhanced greenhouse conditions. *Climate Dynamics*, **13**, 667–680.
- Hoerling M.P., Hurrell J.W., Eischeid J. and Phillips A.S. (2006) Detection and attribution of 20th century Northern and Southern African monsoon change. *Journal of Climate*, **19**, 3989–4008.
- Huntington T.G. (2006) Evidence for intensification of the global water cycle: review and synthesis. *Journal of Hydrology*, **319**, 83–95.
- Hurrell J.W., Kushnir Y., Ottersen G. and Visbeck M. (Eds.) (2003) *The North Atlantic Oscillation: Climate Significance and Environmental Impacts*, Geophysical Monograph No. 134, American Geophysics Union, p. 279.
- IPCC (Intergovernmental Panel on Climate Change) (2007) *Climate Change 2007. The Physical Science Basis*, Contribution of WG I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, Solomon S., Qin D., Manning M., Chen Z., Marquis M.C., Averyt K.B., Tignor M., Miller H.L. (Eds.), Cambridge University Press, Cambridge and New York, p. 1056.
- Karl T.R. and Trenberth K.E. (2003) Modern global climate change. *Science*, **302**, 1719–1723.
- Kiehl J.T. and Trenberth K.E. (1997) Earth's annual global mean energy budget. *Bulletin of the American Meteorological Society*, **78**, 197–208.
- Klein Tank A.M.G. and Können G.P. (2003) Trends in indices of daily temperature and precipitation extremes in Europe, 1946–1999. *Journal of Climate*, **16**, 3665–3680.
- Klein Tank A.M.G., Peterson T.C., Quadir D.A., Dorji S., Zou X., Tang H., Santhosh K., Joshi U.R., Jaswal A.K., Kolli R.K., *et al.* (2006) Changes in daily temperature and precipitation

- extremes in Central and South Asia. *Journal of Geophysical Research*, **111**, D16105, DOI:10.1029/2005JD006316.
- Knowles N., Dettinger M. and Cayan D. (2006) Trends in snowfall versus rainfall for the western United States. *Journal of Climate*, **19**, 4545–4559.
- Kunkel K.E., Easterling D.R., Redmond K. and Hubbard K. (2003) Temporal variations of extreme precipitation events in the United States: 1895–2000. *Geophysical Research Letters*, **30**, 1900, DOI:10.1029/2003GL018052.
- Milly P.C.D., Wetherald R.T., Dunne K.A. and Delworth T.L. (2002) Increasing risk of great floods in a changing climate. *Nature*, **415**, 514–517.
- Mote P.W. (2003) Trends in snow water equivalent in the Pacific Northwest and their climatic causes. *Geophysical Research Letters*, **30**, DOI:10.1029/2003GL0172588.
- Murnane R.J. (2004) Climate research and reinsurance. *Bulletin of the American Meteorological Society*, **85**, 697–707.
- Peterson T.C., Taylor M.A., Demeritte R., Duncombe D.L., Burton S., Thompson F., Porter A., Mercedes M., Villegas E., Semexant Fils R., *et al.* (2002) Recent changes in climate extremes in the Caribbean region. *Journal of Geophysical Research*, **107**, 4601, DOI:10.1029/2002JD002251.
- Santer B.D., Mears C., Wentz F.J., Taylor K.E., Gleckler P.J., Wigley T.M.L., Barnett T.P., Boyle J.S., Brüggermann W., Gillett N.P., *et al.* (2007) Identification of human-induced changes in atmospheric moisture content. *Proceedings of the National Academy of Sciences*, **104**, 15248–15253.
- Schlosser C.A. and Houser P.R. (2007) Assessing a satellite-era perspective of the global water cycle. *Journal of Climate*, **20**, 1316–1338.
- Semenov V.A. and Bengtsson L. (2002) Secular trends in daily precipitation characteristics: greenhouse gas simulation with a coupled AOGCM. *Climate Dynamics*, **19**, 123–140.
- Soden B.J., Jackson D.L., Ramaswamy V., Schwarzkopf D. and Huang X. (2005) The radiative signature of upper tropospheric moistening. *Science*, **310**, 841–844.
- Soden B.J. and Schroeder S.R. (2000) Decadal variations in tropical water vapor: a comparison of observations and a model simulation. *Journal of Climate*, **13**, 3337–3340.
- Soden B.J., Wetherald R.T., Stenchikov G.L. and Robock A. (2002) Global cooling after the eruption of Mount Pinatubo: a test of climate feedback by water vapor. *Science*, **296**, 727–730.
- Sohn B.-J., and Smith E.A. (2003) Explaining sources of discrepancy in SSM/I water vapor algorithms. *Journal of Climate*, **16**, 3229–3255.
- Sun Y., Solomon S., Dai A. and Portmann R. (2007) How often will it rain? *Journal of Climate*, **20**, 4801–4818.
- Thompson D.W. and Wallace J.M. (1998) The arctic oscillation signature in the wintertime geopotential height and temperature fields. *Geophysical Research Letters*, **25**, 1297–1300.
- Trenberth K.E. (1998) Atmospheric moisture residence times and cycling: Implications for rainfall rates and climate change. *Climatic Change*, **39**, 667–694.
- Trenberth K.E. (1999) Conceptual framework for changes of extremes of the hydrological cycle with climate change. *Climatic Change*, **42**, 327–339.
- Trenberth K.E. and Dai A. (2007) Effects of Mount Pinatubo volcanic eruption on the hydrological cycle as an analog of geoengineering. *Geophysical Research Letters*, **34**, L15702, DOI:10.1029/2007GL030524.
- Trenberth K.E., Dai A., Rasmussen R.M. and Parsons D.B. (2003) The changing character of precipitation. *Bulletin of the American Meteorological Society*, **84**, 1205–1217.
- Trenberth K.E., Fasullo J. and Smith L. (2005) Trends and variability in column-integrated water vapor. *Climate Dynamics*, **24**, 741–758.
- Trenberth K.E. and Guillemot C.J. (1996) Physical processes involved in the 1988 drought and 1993 floods in North America. *Journal of Climate*, **9**, 1288–1298.
- Trenberth K.E., Jones P.D., Ambenje P., Bojariu R., Easterling D., Klein Tank A., Parker D., Rahimzadeh F., Renwick J.A., Rusticucci M., *et al.* (2007) Observations: surface and atmospheric climate change. In *Climate Change 2007. The Physical Science Basis*, Contribution of WG 1 to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, Solomon S., Qin D., Manning M., Chen Z., Marquis M.C., Averyt K.B., Tignor M. and H.L., Miller (Eds.), Cambridge University Press, Cambridge, New York, pp. 235–336, plus annex online.
- Trenberth K.E. and Shea D.J. (2005) Relationships between precipitation and surface temperature. *Geophysical Research Letters*, **32**, L14703, DOI:10.1029/2005GL022760.
- Trenberth K.E. and Smith L. (2005) The mass of the atmosphere: a constraint on global analyses. *Journal of Climate*, **18**, 864–875.
- Trenberth K.E. and Stepaniak D.P. (2003a) Co-variability of components of poleward atmospheric energy transports on seasonal and interannual timescales. *Journal of Climate*, **16**, 3691–3705.
- Trenberth K.E. and Stepaniak D.P. (2003b) Seamless poleward atmospheric energy transports and implications for the Hadley circulation. *Journal of Climate*, **16**, 3706–3722.
- Vecchi G.A., Soden B.J., Wittenberg A.T., Held I.M., Leetmaa A. and Harrison M.J. (2006) Weakening of tropical Pacific atmospheric circulation due to anthropogenic forcing. *Nature*, **441**, 73–76.
- Wentz F., Ricciardulli L., Hilburn K. and Mears C. (2007) How much more rain will global warming bring? *Science*, **317**, 233–235.
- Wilby R.L. and Wigley T.M.L. (2002) Future changes in the distribution of daily precipitation totals across North America. *Geophysical Research Letters*, **29**, 7, 10.1029/2001GL013048.
- Yu L.S. and Weller R.A. (2007) Objectively analyzed air-sea heat fluxes for the global ice-free oceans (1981–2005). *Bulletin of American Meteorological Society*, **88**, 527–539.